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Classification of Dartmoor Tors

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Abstract

Fifty-eight Dartmoor tors were evaluated with respect to hypotheses generated to classify granite landforms using field and laboratory measurements of joint type, joint spacing, rock grain size, and rock texture. Landforms on Dartmoor were classified topographically as summit, spur and valleyside tors. The data were evaluated using: 1) non-parametric correlations, 2) joint spacing frequency distributions, 3) variable spatial distributions, and 4) principal coordinates analysis and non-hierarchical classification. Each tor type was defined by each procedures; definitions were similar, but not identical. These definitions were then compared to the hypotheses.

Three hypotheses describe landforms on Dartmoor. An additional hypotheses is indirectly supported because, where the landforms are rare or non-existent, so are their characteristics. These hypotheses, which all describe summit tors, were revised using the combined results of the four approaches; new hypotheses were generated for spur and valleyside tors. Only characteristics common to several procedures and not contradicted by other results were used.

The four types of summit landforms are slightly different, but in general, they have high relative relief, wide vertical joint spacing, and are controlled by vertical joints or by vertical and horizontal joints combined. The rocks are megacrystic and feldspar is abundant. Spur tors generally have narrower vertical joint spacing and low relative relief. The rocks are finer grained, feebly megacrystic or nonmegacrystic, and low in potassium feldspar. Valleyside tors have low relative relief, narrow joint spacing, and horizontal joints control outcrop shape. The rocks are finer grained, feebly megacrystic, and contain small amounts of quartz.

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Three hypotheses describe landforms on Dartmoor. An additional hypothesis is indirectly supported because, where the landforms are rare or non-existent, so are their characteristics. These hypotheses, which all describe summit tors, were revised using the combined results of the four approaches; new hypotheses were generated for spur and valleyside tors. Only characteristics common to several procedures and not contradicted by other results were used.

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Introduction

The underlying rationale for this project was based on observations of granite landforms in different parts of the United States, including South Dakota, Missouri, California, Arizona and Texas. The most important characteristic noted was that many landform shapes, e.g. piles of loose, rounded boulders, tall, slender pinnacles or giant, rounded domes, appeared to be typical of granitic rocks. Variations in joint patterns -- joints are not only ubiquitous but are also very prominent -- appeared to control the different landform shapes. Variations in the distances between joints as well as in the kinds of joints present (vertical or horizontal) appeared to be important. Closer observation suggested that other factors, grain size and rock texture in particular, might also play roles in producing these distinctive shapes. A pattern began to emerge from these observations, and five working hypotheses were formulated. The hypotheses have served as the frame work for field investigations and laboratory analysis; four of them describe landforms present on Dartmoor:

1. Where vertical joints are the controlling joints and are widely spaced, and where the rocks are equigranular, the landforms will be pinnacles, needles or spires.

2. Where vertical joints are the controlling joints and are closely spaced, and where rocks are coarser grained, megacrystic or non-equigranular, the landforms will be whalebacks or tors.

3. Where vertical and horizontal joints are about equal in prominence and are widely spaced, and where the rocks are equigranular, the landforms will be castellated or blocky.

4. Where horizontal joints are controlling joints and are closely spaced, the landforms will be lamellar.

Although it is highly likely that other factors, such as composition, are equally important, their effects on landform shape were not visually obvious and as a result, they were not included in the hypotheses. There is some confusion in terminology in these hypotheses (e.g. whalebacks and tors are not in fact the same), but this confusion, also noted by Gerrard (1988), is common in the literature.

There are many examples in the vast literature on granite landforms (Twidale, 1982; Ehlen, 1990) that relate structural, petrographic and other geomorphic characteristics to landform. The relation between joints and granite landforms, for instance, is mentioned in many papers. Joints are usually described as controlling the general outlines of the landforms. Water enters the rock through the joints, which become locations for chemical weathering, which produces the characteristic rounding of the landforms (e.g. Linton, 1955; Waters, 1957; Brunsden, 1964; Thomas, 1974). Other workers define certain landforms in terms of joint spacing, e.g. domes develop only where joints are very widely spaced (e.g. Ormerod, 1859, 1869; Mabbutt, 1952; Twidale, 1964, 1982). Ranges for joint spacing are occasionally given, but these figures appear to be based on casual observation, not measurement (e.g. de la Beche, 1839; Caine, 1967; Brunsden and Gerrard, 1970). Most of this work refers to vertical or steeply-dipping joints: horizontal joints are typically described as sheeting joints, and there is little to no reference to the systematic horizontal joints that are an essential part of the characteristic orthogonal joint pattern in granitic rocks. Spacing between horizontal joints is typically described as increasing with depth (e.g. Jahns, 1943; Oen, 1965; Bloom, 1978; Hawkes, 1982).

Chapman and Rioux (1958), Dumanowski (1964) and Snow (1968) present quantitative data on joint spacing, but only in passing. Thorpe (1979), however, measured joint spacing and distribution in an underground cavity in the Stripa granite in Sweden as did Bourke et al. (1981) and Bourke et al. (1982) in bore holes in the Carnmenellis granite in Cornwall. Whittle (1989) presented more recent and comprehensive data, both surface and subsurface, collected on the Carnmenellis granite in conjunction with the Hot Dry Rock geothermal project.

Only Gerrard (1974, 1978) and Ehlen and Zen (1990) have reported detailed fracture spacing data. Gerrard (1974) described the joint patterns on Dartmoor and evaluated the relations between jointing and the location of tors. By comparing joint spacings, slope angle and tor height of tors on Bodmin Moor as well as Dartmoor, Gerrard (1978) determined that the tors occur where joints are closely spaced in comparison to those in the surrounding area, but not so closely spaced that the rock is completely weathered and removed. Ehlen and Zen (1990) reported fracture spacings and modal analyses for several types of granitic rocks in the United States and on Dartmoor. Outcrop descriptions and locations are provided; there is no analysis or interpretation.

The mineralogical and textural characteristics of granitic rocks also affect landform. Lithologic or petrographic boundaries often coincide with landform boundaries (e.g. Demek, 1964; Eggler et al., 1969; Jeje, 1973). Dumanowski (1964, 1968), Brook (1978), Robb (1979) and Pye et al. (1986) determined that inselbergs tend to contain abundant potassium feldspar whereas rocks in areas without inselbergs tend to be low in potassium feldspar. Gibbons (1981) and Pye et al. (1984) found porphyritic rocks are more resistant than nonporphyritic rocks. Gibbons (1981) also found that tor densities increased in coarser-grained rocks.

Landform Classifications

In his classic paper, Linton (1955) referred to tors according to topographic position, e.g. summit tors, spur tors, and in addition, offered a series of hypotheses for the formation of certain types of landforms, including tors, stacks, and buttresses, some of which are topographically dependent. He considered that these landforms are formed by the two-stage process. Linton did not explain how the different landform types differ with respect to composition, grain size, or texture, but stated that "There is every indication that the main factor at work on Dartmoor ...is the spacing of joints." (p. 474).

Gerrard (1974) used a classification similar to Linton's in his evaluation of the importance of jointing to the evolution of the Dartmoor tors. He classified the tors as summit tors, valleyside and spur tors, and emergent tors. Including tors on Bodmin Moor, Gerrard (1978) determined that the tors fall into two groups: 1) summit and valleyside tors and 2) emergent tors. Joints are more closely spaced and spacing is more variable in summit and valleyside tors.

Twidale (1980, 1981, 1982) has also classified granite landforms. His work primarily concerned inselbergs, which he separated into three, genetically-related types: bornhardts (domes), castle koppies, and nubbins. Castle koppies develop in massive bedrock on what will be large-radius domes. Nubbins are block- or boulder-strewn residuals that develop on what will be small-radius domes. Jointing is important in that sheeting structure is dominant in nubbins whereas, although fractures are few in castle koppies, orthogonal joints are dominant. Both castle koppies and nubbins develop subsurface, but under slightly different climatic conditions. The Dartmoor tors are castle koppies in Twidale's classification.

The purpose of this study is thus to look at jointing as well as rock texture, composition, grain size, and various geomorphic factors, to better define the granite landforms on Dartmoor. The hypotheses listed above formed the basis for this investigation. Dartmoor was selected because of its classic suite of landforms and because of the work done previously by Linton and Gerrard which refers specifically to Dartmoor. In addition, there is a large body of literature describing various aspects of the Dartmoor landforms.

Variable Definitions and Procedures

The twenty-three variables chosen for study comprise three groups: geomorphic variables, petrographic variables, and structural variables. All variables have been defined previously (Ehlen 1991, 1992, in prep), but the definitions are repeated here for ease of reference. The methods by which some of the data were obtained are briefly described for the same reason. Although most variables are used in all data analysis procedures, the data are handled differently in each procedure, and thus are not necessarily expressed in the same way.

Geomorphic Variables

Four landform types, summit tors, spur tors, valleyside tors and pinnacles, were identified in the field and from 1:25,000 scale topographic maps. Although "tor" is a landform type to be tested in the hypotheses, this term is used in the classification because that is what the landforms are called on Dartmoor (an excellent example of confused terminology!). A topographic classification is used because similar classifications were described by Linton (1955) and used by Gerrard (1974, 1978). This topographic classification does not correspond to the landforms defined in the hypotheses, or necessarily to those described by Linton or Gerrard, but small domes, lamellar tors, blocky/castellated tors and pinnacles are all present on Dartmoor and are included within these topographic categories. Table 1 defines the landform types in the topographic classification and Figure 1 shows the typical topographic positions of summit, spur and valleyside tors. Pinnacles, which are rare (only one is included in this sample), occur in both summit and spur positions.

Tor shape is usually controlled by one of three joint sets -- an horizontal set that forms the top of the tor, and vertical sets 1) perpendicular to the face of the tor forming its sides, and 2) parallel to and forming the face of the tor. The variable "joint control" identifies which type of joint, i.e. vertical or horizontal (see below), appears most important to the shape of the tor. If neither type is dominant, joint control is equal. Joint control was determined visually.

Relative relief, determined from 1:25,000 scale topographic maps, is defined as the vertical distance between the outcrop and the nearest main stream within a horizontal distance of 800 m. Gerrard (1974) defined and used relative relief in this way in his study of Dartmoor tors.

Petrographic Variables

Grain size and composition were determined microscopically on stained, cut slabs (see Ehlen and Zen, 1986, for the procedure). Grain size was determined only on major minerals, i.e. quartz, potassium feldspar and plagioclase feldspar. The modal analyses included quartz, potassium feldspar, plagioclase feldspar and tourmaline. Potassium feldspar grain size and modal percent refer to groundmass; the large megacrysts are considered separately.

Clay, probably kaolinite, was identified in thin section (E-an Zen, 1988, oral communication). The presence of clay may be an indicator of degree of weathering such that its presence may affect outcrop size and/or joint spacing. Tourmaline veins, which occur in closely-spaced secondary vertical joints, typically form zones that are more weathered than the surrounding rock. Presence or absence of tourmaline veins, which might provide insight into susceptibility to weathering, was determined in the field. Schorl is an intergrowth of quartz and tourmaline. It occurs as small, usually rounded blebs that are very hard, and that are distributed unevenly throughout the rocks. Presence or absence, which might affect joint spacing, was determined in the field and visually from cut slabs.

Rock texture may also affect joint spacing and frequency; three variables address textural characteristics of the rocks. Megacryst counts for the variable "number of megacrysts" ~~were~~ done in the field. The number of megacrysts longer than 2.5 cm within a standard botanist's quadrat (0.25 square meter) on a typical surface was recorded. The variable "percent megacrysts" was determined microscopically and is thus on a volume basis. The variable "grain size distribution" was determined visually from the stained, cut slabs. The rocks were classified as equigranular, nonequigranular or megacrystic. Only potassium feldspar megacrysts are included in these three variables. Large quartz and plagioclase crystals are present, but they are less than 2.5 cm in length.

Structural Variables

Joint spacing is the distance between successive joints in a given joint set, measured normal to the planes of the joints along a linear traverse of continuous outcrop. A joint set is a collection of individual joints that are essentially parallel with similar inclination. Primary joints are long, usually open, tor-shape-controlling joints that typically cross other joint traces. Secondary joints are shorter joints, local in extent, that rarely cross other joint traces. No genetic connotation is implied by these terms. Vertical joints are defined as dipping 70° or more, whereas horizontal joints dip 25° or less. Joints in the intermediate category are rare on Dartmoor.

Joint spacings were measured between approximately 7000 joints in 185 joint sets at 58 sample sites (Figure 2). The data are reported in Ehlen and Zen (1990). Mean joint spacing for a sample site was determined by averaging the spacings for all joints of one type regardless of joint set. Ratios between horizontal and vertical joints for both primary and secondary joints are also included as variables. The ratios were calculated using mean joint spacings.

Data Analysis

Introduction

Four approaches were used to evaluate the data: 1) statistical correlations; 2) joint spacing frequency distributions, 3) spatial distributions of the individual variables and 4) multivariate statistical analyses. Each section below includes a brief description of the procedures used, a note as to which variables were used and in what form, and a summary of the results of the analysis. Some of these results were published previously; sources are cited where appropriate. Because the variables differ slightly among procedures, the results described below for each procedure do not necessarily agree. For example, clay was included in the analysis of correlations, so presence or absence is included in the descriptions of summit and spur tors. It was not included in the analysis of frequency histograms, so does not appear in the tor descriptions for this procedure.

Correlations

Analysis of statistical correlations comprised the initial evaluation of the multitude of possible interrelationships between these variables. The non-parametric procedure Spearman's rank correlation coefficient (rho) was used because 1) it allows inclusion of binary and nominal variables, and 2) ranks are not necessarily affected by closed or constant-sum data, i.e. percentages (Rock, 1988). The following discussion refers to significant correlations at the 95% confidence level unless otherwise noted. Spell out

All variables were used in this analysis. For the binary variables and the coded nominal variables, a positive correlation is with a higher number. For the binary variables, schorl, clay and tourmaline veins, positive correlation is associated with absence. High positive correlations for the coded variables define relations with summit tors, megacrystic rocks and equal (horizontal and vertical) joint control of tor shape. Low negative correlations for the coded variables define relations with spur tors, equigranular rocks, and horizontal joint control of tor shape.

Only summit and spur tors could be evaluated using this procedure: the coding system for the landforms was such that valleyside tors always have intermediate characteristics between spur and summit tors. Furthermore, pinnacles were excluded because of their limited occurrence; there is only one pinnacle among the 58 sample sites. Two types of characteri~~s~~zation are possible: 1) direct relations based on significant correlations with landform and 2) indirect relations based on correlations between other variables, one of which is significantly correlated with landform.

Analysis of significant correlations indicates that summit tors have high relative relief and wide vertical joint spacing. Their shapes are usually controlled by vertical joints alone or horizontal and vertical joints in combination. The rocks are strongly megacrystic, schorl is typically absent, and tourmaline veins are rare. Indirect relations indicate summit tors are likely to have widely-spaced horizontal joints and ~~to be~~ composed of coarse-grained rock that is high in plagioclase and tourmaline, but low in quartz and potassium feldspar. Clay is likely to be absent.

Spur tors, on the other hand, have lower relative relief and narrower vertical joint spacing. They are controlled by horizontal joints. The rocks are feebly megacrystic or equigranular in texture and contain both schorl and tourmaline veins. Indirect relations indicate horizontal joints in spur tors are likely to be closely spaced and that the rocks are likely to be finer grained, to contain clay, and to have low tourmaline and plagioclase abundances and high quartz and potassium feldspar abundances.

Joint Spacing Frequency Distributions

The analysis of the relations defined by the frequency histograms can be found in Ehlen (1991). Frequency distributions were used to determine how the variables affected joint spacing (e.g. is there a difference in joint spacing between the <1 mm grain size category and the 1-2 mm grain size category?). The variables used, all of which were coded, are: joint type, grain size, grain size distribution, number of megacrysts, relative relief, and landform. These variables either appeared in the hypotheses or were significantly correlated. The variables were plotted in combination; Figure 3 shows one frequency histogram as an example; all histograms can be found in Ehlen (1989). The frequency distributions for the variable combinations were compared using chi square so that significant differences could be identified between pairs of spacing distributions. All references to joint spacings are to mean spacings.

Joint spacing is widest in summit tors. Mean spacing for primary horizontal joints is 72.9 cm; for secondary horizontal joints, 12.9 cm, and for primary vertical joints, 260.3 cm. Horizontal joint spacing is similar to that in spur tors and both vertical and horizontal joint spacing are more like that in spur tors than in valleyside tors. Joint spacing in summit tors is very different from that in pinnacles. Summit tors with coarser grain have intermediate joint spacing. Finally, summit tors contain the largest numbers of megacrysts. Summit tors that have high relative relief contain the most abundant megacrysts.

Joint spacing is second widest in spur tors. Mean primary vertical joint spacing is 257.9 cm; primary horizontal joint spacing, 72.7 cm; and secondary horizontal joint spacing, 12.2 cm. Secondary vertical joint spacing, however, is the widest among the four types of tors (69.6 cm). Horizontal joint spacing in spur tors is very similar to that in summit tors, and spur tors are more like summit tors than valleyside tors with respect to vertical joint spacing. Like summit tors, joint spacing is very different from that in pinnacles. In coarser-grained spur tors, joint spacing is narrower than it is in either coarser-grained summit tors or valleyside tors, but becomes wider with increasing numbers of megacrysts. In this respect, spur tors are similar to valleyside tors.

Valleyside tors, which are controlled by secondary vertical joints, have the narrowest joint spacing of the three major tor types: primary vertical joints, 256.9 cm; secondary vertical joints, 47.9 cm; primary horizontal joints, 57.4 cm; and secondary horizontal joints, 11.2 cm. Valleyside tors are very different from pinnacles with respect to both kinds of joints, like summit and spur tors, but they are also very different from spur and summit tors with regards to vertical and horizontal joint spacing. In addition, valleyside tors always have the narrowest joint spacing regardless of relative relief. Joint spacing becomes wider, however, as the rock becomes coarser grained. Finally, joint spacing in valleyside tors becomes wider with increasing numbers of megacrysts, similar to spur tors.

The one pinnacle is controlled by very closely-spaced secondary vertical joints and has the narrowest vertical joint spacing of the four tor types: primary spacing is 178.1 cm and secondary spacing is 28.1 cm. As stated above, pinnacles are very different from all other types of tors with respect to both vertical and horizontal joints.

Spatial Patterns

Spatial patterns of the variables were identified by visual analysis of contour maps showing the distribution of each variable over Dartmoor (Ehlen, 1992). These maps were generated using the TIN module of ARC/INFO. Similarities between variable patterns were determined by overlaying the contour maps on a light table. Like the correlation analysis, two types of characterisations are possible: 1) those determined by overlaying a variable map onto the landform map and 2) those determined by overlaying two variable maps, only one of which exhibits a definable pattern when compared directly to the landform map. Figure 4 shows the distribution of plagioclase feldspar on Dartmoor as an example; additional maps can be found in Ehlen (1989, 1992). All variables except the two joint spacing ratios were used in this analysis. Pinnacles were again excluded.

Analysis of the spatial patterns of the variables indicates that summit tors contain widely-spaced primary vertical joints (usually >300 cm) and horizontal joint spacing is intermediate to wide: primary spacing ranges from 60-80 cm and secondary spacing is >10 cm. Summit tors occur where relative relief is high (mean: 125.7 m). The rocks contain abundant feldspar, usually >30%

potassium feldspar and >18% plagioclase. They are strongly megacrystic (usually >15 and >15% megacrysts) as well as coarse grained (>2 mm). Schorl is often present. Spatial relations between other variables suggest that summit tors may be controlled by vertical joints, and are likely to contain abundant quartz and no tourmaline veins.

Joint spacing is narrow in spur tors. Primary vertical joint spacing is <200 cm; secondary vertical spacing ranges from 50-75 cm; primary horizontal joint spacing is usually <60 cm; and secondary horizontal spacing is <10 cm. Relative relief is typically intermediate (mean: 115.4 m). The rocks in spur tors are fine grained (<1 mm) and often contain tourmaline veins. Texture is feebly megacrystic, generally with <5% megacrysts. Spatial relations between other variables suggest that quartz abundance may be high and tourmaline abundance is likely to be low. Tor shape may be controlled by vertical joints and rock texture is likely to be equigranular.

In valleyside tors, primary vertical joint spacing is narrow (<300 cm), but horizontal joint spacing is wide. Primary horizontal joint spacing ranges from 60-200 cm, and secondary spacing is usually >10 cm. Valleyside tors are controlled by horizontal joints, and relative relief is typically low (mean: 72.9 m). Potassium feldspar tends to be coarse grained (>2 mm), but overall, the rocks have fine to intermediate grain size (<2 mm). Potassium feldspar abundance is low (<31%) and quartz abundance is intermediate (30-33%). Spatial relations between other variables suggest that plagioclase feldspar may be abundant, but tourmaline abundance is likely to be low; tourmaline veins are likely to be absent. Rock texture ranges from equigranular to very feebly megacrystic.

Multivariate Analysis

Ordination and classification procedures were used to identify similarities among tors (Ehlen, in prep). Principal coordinates analysis, a Q-mode procedure, was chosen for ordination because 1) it accepts nominal and ordinal variables and 2) is distribution free. With a Q-mode analysis, the data are viewed from the perspective of the objects, or in this case, the sample sites. The non-hierarchical classification is also nonparametric and allowed inclusion of nominal and ordinal variables.

Frequency histograms were used to evaluate the results of classification and ordination to determine the statistical significance of the results. Joint spacings for each set in each tor in each cluster of sample sites were identified and the frequency distributions were determined. As described above, chi square was used to determine whether or not the clusters were significantly different from each other with respect to joint spacing. The groups along each of the important coordinates were also compared in this manner.

Five clusters were identified using principal coordinates analysis and the non-hierarchical classification (Figure 5). It is impossible to characterise each tor type as was done for the procedures described above, because most tor types occur in more than one cluster. Only the clusters are thus described. All variables except clay were used.

Tors in the first cluster occur mainly south of a line connecting Great Mis Tor and Bell Tor (see Figure 1 for the locations of specific tors). They are characterised by medium to high numbers of megacrysts, medium- to coarse-grained feldspar, narrow to intermediate vertical joint spacing, medium to high secondary joint spacing ratios, and low to intermediate quartz abundances. Tourmaline veins are present, but there is generally no schorl. Most of the tors are summit tors (e.g. Roos Tor), but some spur tors are present as well (e.g. Mel Tor). The single pinnacle occurs in this cluster (Great Staple Tor).

Members of the second cluster are present throughout Dartmoor, except in the south. Many of them are lamellar, e.g. Great Links Tor. They are characterised by fine- to medium-grained feldspar, widely-spaced vertical joints, low secondary joint spacing ratios, and low to intermediate quartz abundances. Tourmaline veins are absent.

The two sample sites in Cluster 3 have no megacrysts and plagioclase feldspar is fine grained. Vertical joint spacing is narrow. The tors occur in the northwest and east.

Most of the tors in the fourth cluster occur in the east. They have medium to high numbers of megacrysts, medium- to coarse-grained feldspar, intermediate vertical joint spacing, low quartz abundances, moderately to highly abundant plagioclase, and form summit tors (e.g. Hound Tor). Schorl is typically present and tourmaline veins are absent.

The fifth cluster is the largest and is present throughout Dartmoor except in the northeast. These tors are often located near the granite boundary (e.g. Pew Tor) and many are altered or reddened (e.g. Doe Tor). They are characterised by few megacrysts, fine- to medium-grained feldspar, narrow to intermediate vertical joint spacing, medium to high secondary joint spacing ratios, low to intermediate plagioclase abundances, and form summit and valleyside tors (e.g. Rippon Tor and Hen Tor, respectively). Tourmaline veins are typically present.

Comparisons of Results to Hypotheses

For ease of reference, the four hypotheses are repeated here:

1. Where vertical joints are the controlling joints and are widely spaced, and where the rocks are equigranular, the landforms will be pinnacles, needles or spires.

2. Where vertical joints are the controlling joints and are closely spaced, and where rocks are coarser grained, megacrystic or non-equigranular, the landforms will be whalebacks or tors.

3. Where vertical and horizontal joints are about equal in prominence and are widely spaced, and where the rocks are equigranular, the landforms will be castellated or blocky.

4. Where horizontal joints are controlling joints and are closely spaced, the landforms will be lamellar.

Correlations

Only minimal support is given to three hypotheses by the analysis of correlations: no support is given for hypothesis 2. The summit tor category provides some support for hypothesis 3. Joint control can be by vertical and horizontal joints combined and both types of joints are widely spaced in summit tors. However, joint control can also be by vertical joints alone, and the rocks are megacrystic, not equigranular. The characteristics of spur tors give support to hypothesis 4: joint control is by horizontal joints, which are closely spaced, and rock texture ranges from equigranular to feebly megacrystic. All lamellar tors on Dartmoor, however, are summit tors, not spur tors.

Joint Spacing Frequency Distributions

As with the analysis of correlations, the frequency histograms provide some support for three hypotheses. As above, no support was given to hypotheses 2.

Pinnacles are controlled by vertical joints as predicted by hypothesis 1, but the joints are closely spaced, not widely spaced as required. It is possible, however, that the very scarcity of the combination of characteristics defined by hypothesis 1 explains why there are so few pinnacles on Dartmoor, which supports the hypothesis in reverse!

Dartmoor summit tors, as defined by analysis of the frequency histograms, are most like the castellated, blocky landforms of hypothesis 3. They generally have wide joint spacing and are controlled equally by horizontal and vertical joints, but most summit tors are megacrystic, not equigranular as required by the hypothesis. The lamellar landforms of hypothesis 4 are included among the summit tors on Dartmoor, but the characteristics of summit tors defined by analysis of the frequency histograms do not match those of hypothesis 4. Specifically, summit tors have very wide horizontal joint spacing; the most closely-spaced horizontal joints are found in valleyside tors, none of which are lamellar.

Spatial Patterns

Again, only limited support is given for the hypotheses by analysis of spatial patterns. Three hypotheses are partially supported. No support is given for hypotheses 1: pinnacles could not be evaluated because there is only one.

There is some support for hypothesis 2. Closely-spaced vertical joints are associated with spur and valleyside tors and with finer-grained rocks, but vertical joint control is associated with summit tors having coarse grain and wide joint spacing. The rocks of valleyside tors are feebly megacrystic or equigranular and those in spur tors are equigranular; only rocks in summit tors are sufficiently megacrystic to meet the requirements of hypothesis 2.

Spatial patterns also give some support for hypothesis 3 in that widely-spaced joints are associated with summit tors. The rocks of these tors, however, are strongly megacrystic, and joint control tends to be by vertical joints alone. Furthermore, areas of equigranular rock on Dartmoor are associated with closely-spaced horizontal joints.

With reference to hypothesis 4, only valleyside tors are controlled by horizontal joints. Horizontal joint spacing in these tors is wide and the rocks are either equigranular or feebly megacrystic. Horizontal joints are closely spaced only in spur tors, but control here is by vertical joints. As stated above, all lamellar tors on Dartmoor are summit tors, and analysis of spatial patterns suggests that summit tors exhibit wide horizontal joint spacing.

Multivariate Analysis

Three hypotheses are fully supported by the multivariate analyses and one receives no support. None of the five clusters of tors identified using the multivariate procedures have the characteristics defined by hypothesis 1: there is only one pinnacle, there are few tors where widely-spaced vertical joints control shape and there are only small areas of equigranular rock. None of these characteristics are sufficiently widespread to define a group.

Hypothesis 2 fits the conditions of clusters 1 and 3 with respect to closely-spaced vertical joints. However, cluster 3 is fine-grained and equigranular, so it cannot be compared further. Cluster 1, on the other hand, supports this hypothesis -- the rocks are coarse grained and megacrystic, and most of the landforms are summit tors of the type initially envisioned as tors, such as the eastern block of Haytor. Interestingly, the members of cluster 3 are fine-grained parts of tors included in cluster 1. It is possible that cluster 4 may also support this hypothesis: the rocks are strongly megacrystic and coarse grained. Vertical joint spacing is, however, intermediate.

Hypothesis 3 is supported by cluster 5. These tors have by narrow to intermediate vertical joint spacing and an intermediate secondary ratio, indicating horizontal and vertical joint spacing are not dissimilar in most tors in the cluster. The rock is equigranular, and both summit and valleyside tors occur. The summit tors include South Hessary Tor, Combestone Tor, and Wild Tor, among others, which are blocky.

Hypothesis 4 is supported by cluster 2. This cluster contains all the lamellar tors on Dartmoor as well as other tors with closely-spaced horizontal joints. Examples of the latter are Scorhill Tor, Elsford Rock and Lower Dunna Goat. Horizontal joints are not specified among the cluster descriptors, but the wide vertical joint spacing and low secondary ratio indicate horizontal joint spacing must be narrow. The rocks are generally finer grained.

Conclusions

The hypotheses were revised to characterise the Dartmoor tors employing the results presented above. Although the descriptions of each tor type using the different procedures are not identical, the similarities among the results allow the hypotheses to be expanded and refined using the topographic classification. Only those characteristics that are common to several procedures and not contradicted by the results of other procedures are included in the revisions.

The hypothesis referring to pinnacles must be left as it is: only one pinnacle was measured and as a result, pinnacles were not included in two of the analyses. The remaining three hypotheses, those describing tors, castellated landforms and lamellar landforms, occur within the summit landform category in the landform classification used on Dartmoor, allowing this category to be subdivided. Wherever possible, general terms are quantified. The revisions are:

Summit Landforms generally have high relative relief (mean 125.7 m), are megacrystic (>15 and/or 15%), have wide vertical joint spacing (primary joints >300 cm) and are usually controlled by vertical joints or by vertical and horizontal joints combined. Feldspar is usually abundant (>30% potassium feldspar; >18% plagioclase). There are four types of summit landforms:

> **Tors** are controlled by vertical joints and have narrow to intermediate vertical joint spacing. Horizontal joints are more widely spaced. The rocks are moderately to strongly megacrystic and are coarse grained. Quartz abundance is intermediate. (Type Tor: Roos Tor; Figure 6(A))
>
> **Lamellar Landforms** occur where horizontal joints are closely spaced and vertical joints are very widely spaced. The rocks are fine to medium grained and are usually equigranular or, at best, feebly megacrystic. (Type Tor: Branscombe's Loaf; Figure 6(B))
>
> **Blocky Landforms** are controlled equally by horizontal and vertical joints. Vertical joint spacing is narrow to intermediate and horizontal spacing is intermediate. The rocks are feebly megacrystic and fine to medium grained. Plagioclase abundance is low to intermediate. (Type Tor: Combestone Tor; Figure 6(C))
>
> **Castellated Landforms** are controlled equally by horizontal and vertical joints. Vertical joint spacing is intermediate. The rocks are strongly megacrystic and coarse grained. Plagioclase is abundant. (Type Tor: Hound Tor; Figure 6(D))

The following descriptions are proposed for spur and valleyside landforms and will form hypotheses for further work in other granitic terranes.

Spur Landforms generally have narrower vertical joint spacing (primary joints <200 cm; secondary joints 50-75 cm) and occur where relative relief is low (mean 115.4 m). The rocks are fine grained (<1 mm) and feebly megacrystic (<5%) or equigranular. Potassium feldspar abundance is low. (Type Tor: Littaford Tors; Figure 7)

Valleyside Landforms occur where relative relief is low (mean 72.9 m) and have narrow joint spacing (primary vertical joints <300 cm). Horizontal joints control tor shape. The rocks are finer grained (<2 mm) and feebly megacrystic. Quartz abundance is low. (Type Tor: Black Tor; Figure 8)

The revisions and new hypotheses refer to true granite, and only further testing will show whether these characteristics are typical of other granitic rocks as well (e.g. granodiorite, quartz diorite). Similarly, the quantitative descriptors determined by analysis of spatial patterns refer only to the Dartmoor tors. Until the same hypotheses and procedures are applied to granite landforms in other areas, it is not known whether these values are universal or peculiar to Dartmoor.

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List of Tables

Table 1: Landform Classification

Tor Type:	Tor Size:	Tor Location:	Nearby Slopes:
Summit	large	on hill and ridge crests	gentle
Spur	typically small	ends of ridges or spurs	gentle
Valleyside	large and massive to small ledges	along valley sides, below the break in slope, usually on upper slopes	steep above and below
Pinnacle	tall in relation to girth	ends of ridges or spurs or on summits	gentle or steep below

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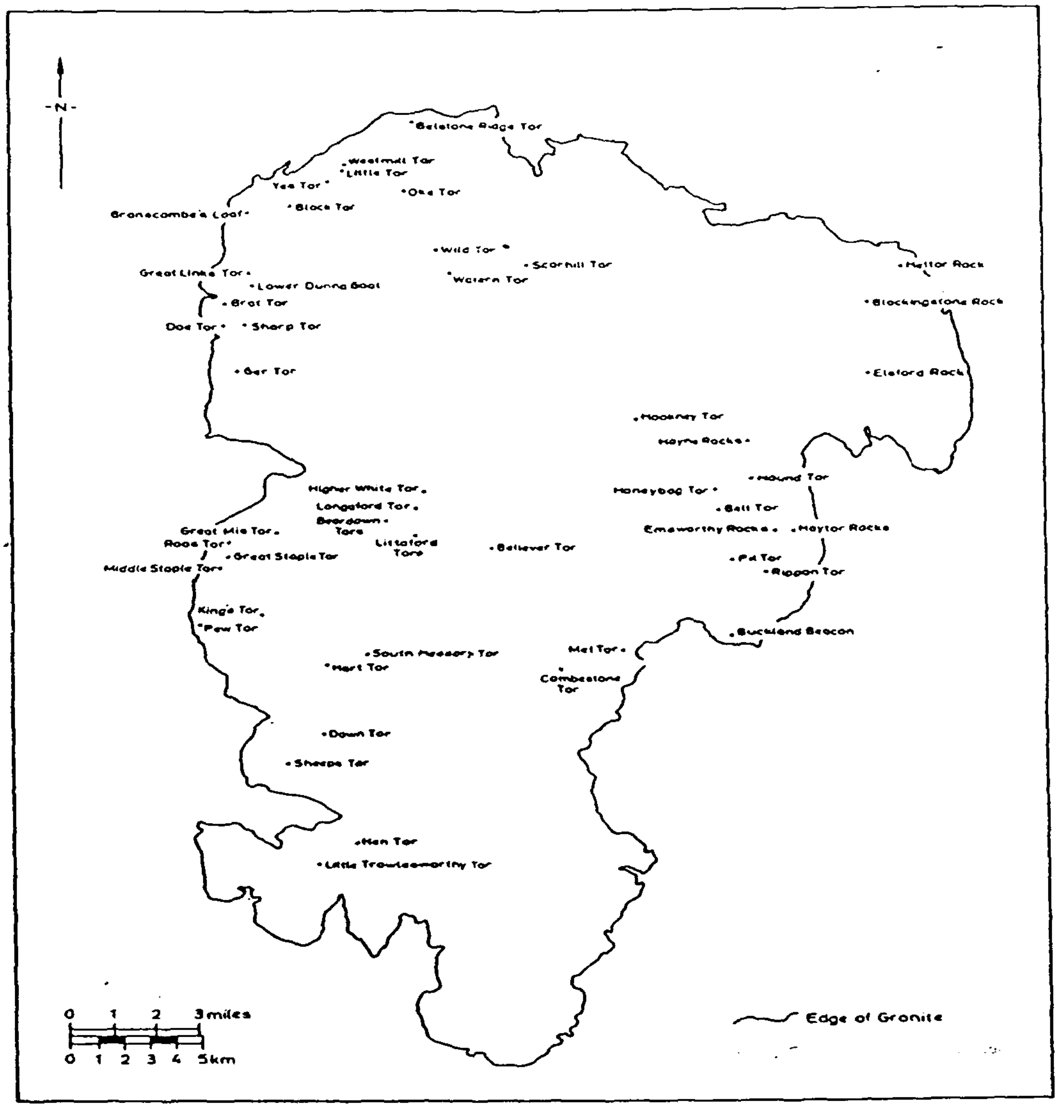

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Belstone Ridge Tor
Westmill Tor
Little Tor
Yes Tor
Oke Tor
Black Tor
Great Links Tor
Lower Dunna Goat
Brat Tor
Doe Tor
Sharp Tor
Ger Tor
Wild Tor
Scorhill Tor
Watern Tor
Blackingstone Rock
Elsford Rock
Hound Tor
Honeybag Tor
Bell Tor
Emsworthy Rocks
Haytor Rocks
Rippon Tor
Buckland Beacon
Higher White Tor
Longaford Tor
Beardown Tors
Littaford Tors
Bellever Tor
Great Mis Tor
Roos Tor
Great Staple Tor
Middle Staple Tor
Kings Tor
Pew Tor
South Hessary Tor
Hart Tor
Mel Tor
Combestone Tor
Down Tor
Sheeps Tor
Hen Tor
Little Trowlesworthy Tor
0 1 2 3 miles
0 1 2 3 4 5 km
Edge of Granite

Figure 1

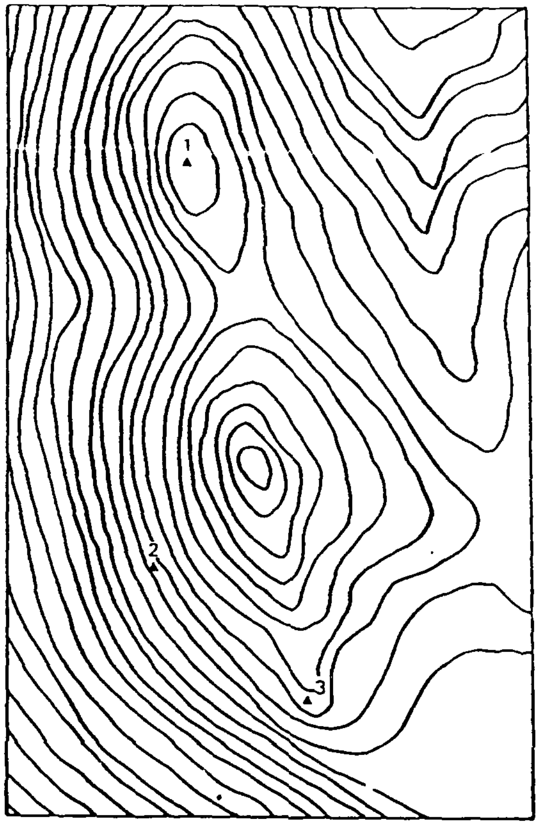
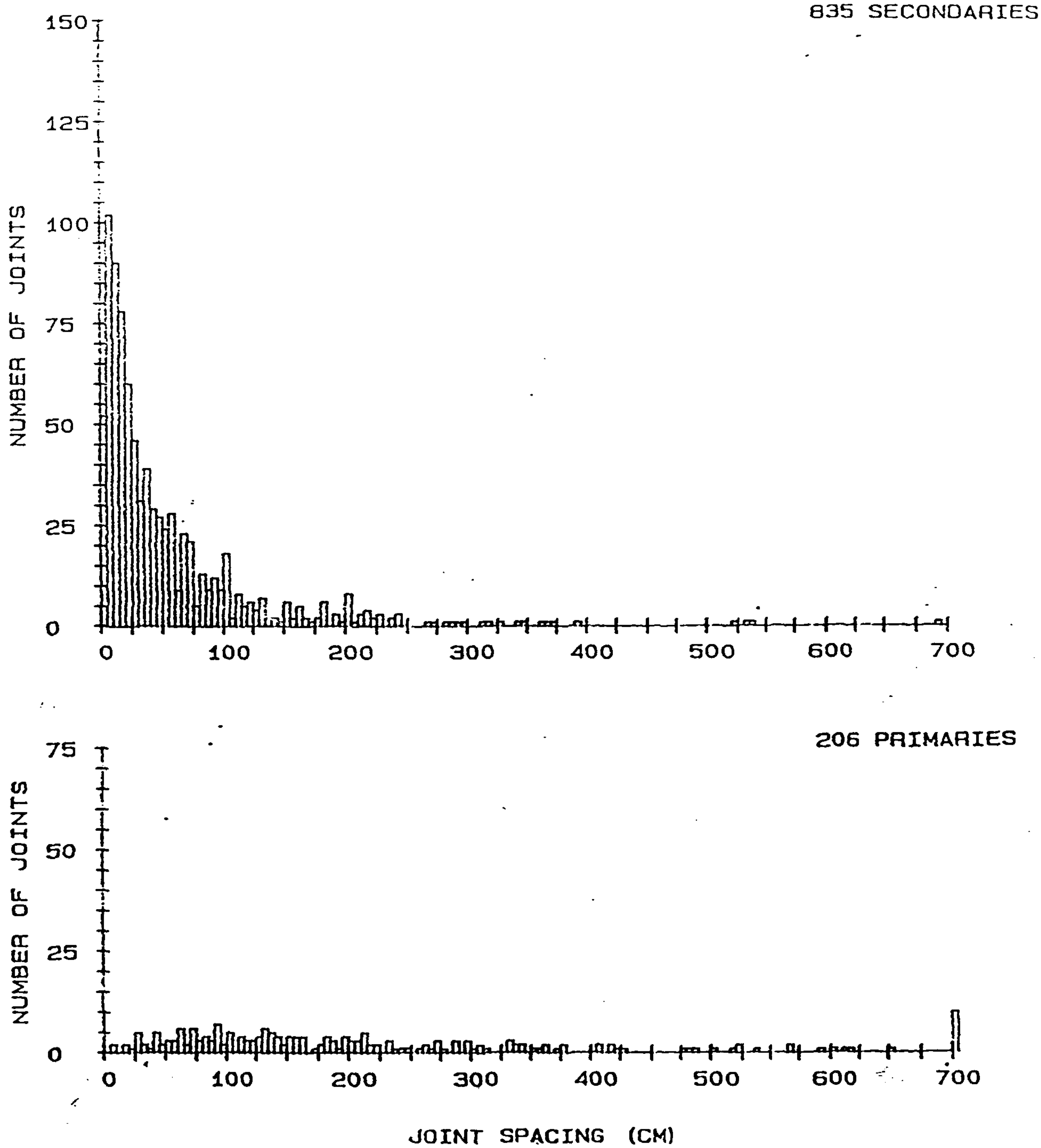
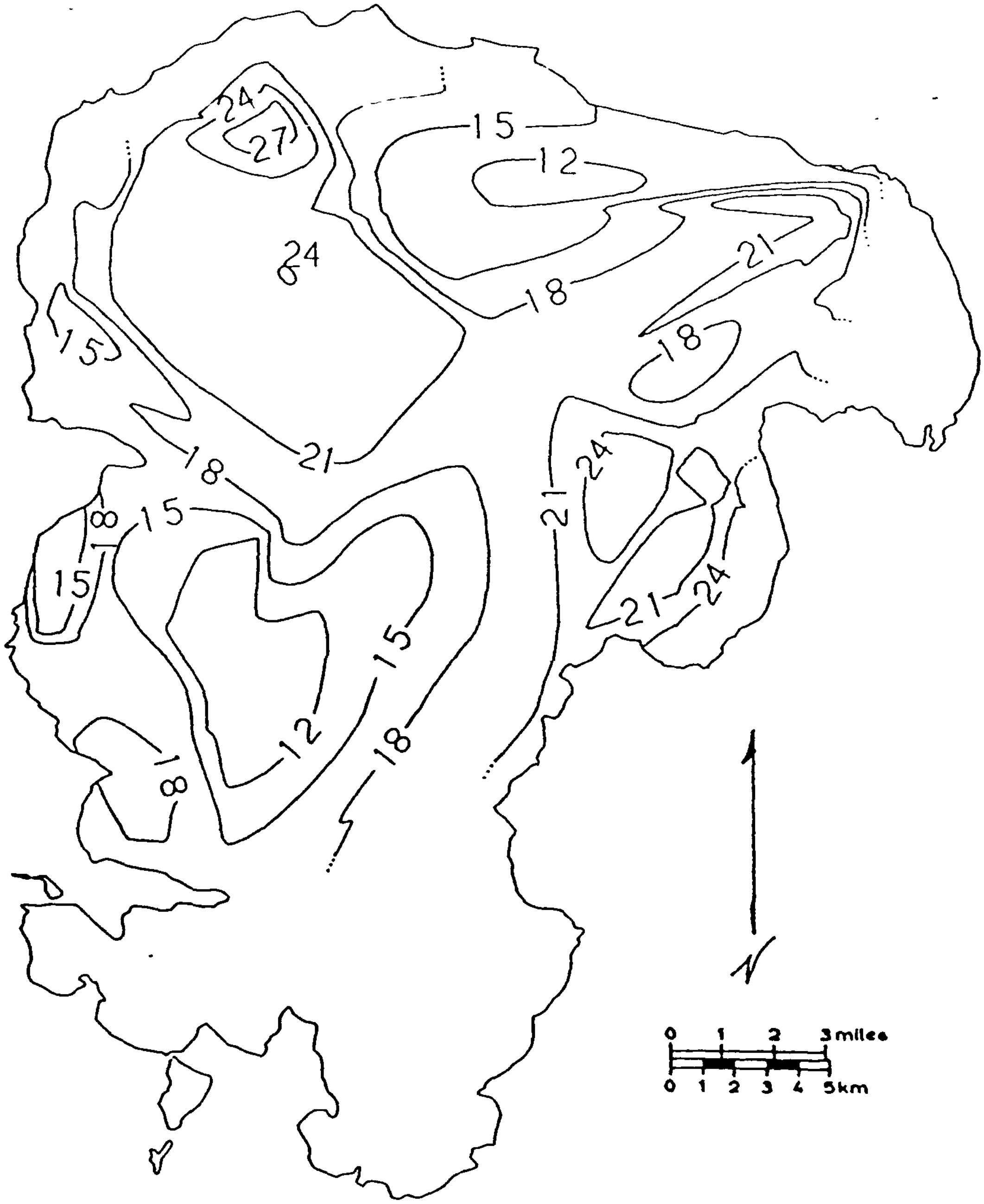


Figure 9

DARTMOOR, ENGLAND
VERTICAL JOINTS
NO. MEGACRYSTS: 0-2

	MIN	MAX	MEAN	MED	MODE
P	6	1575	229.3		700 - 705
S	2	690	54.1		5 - 10





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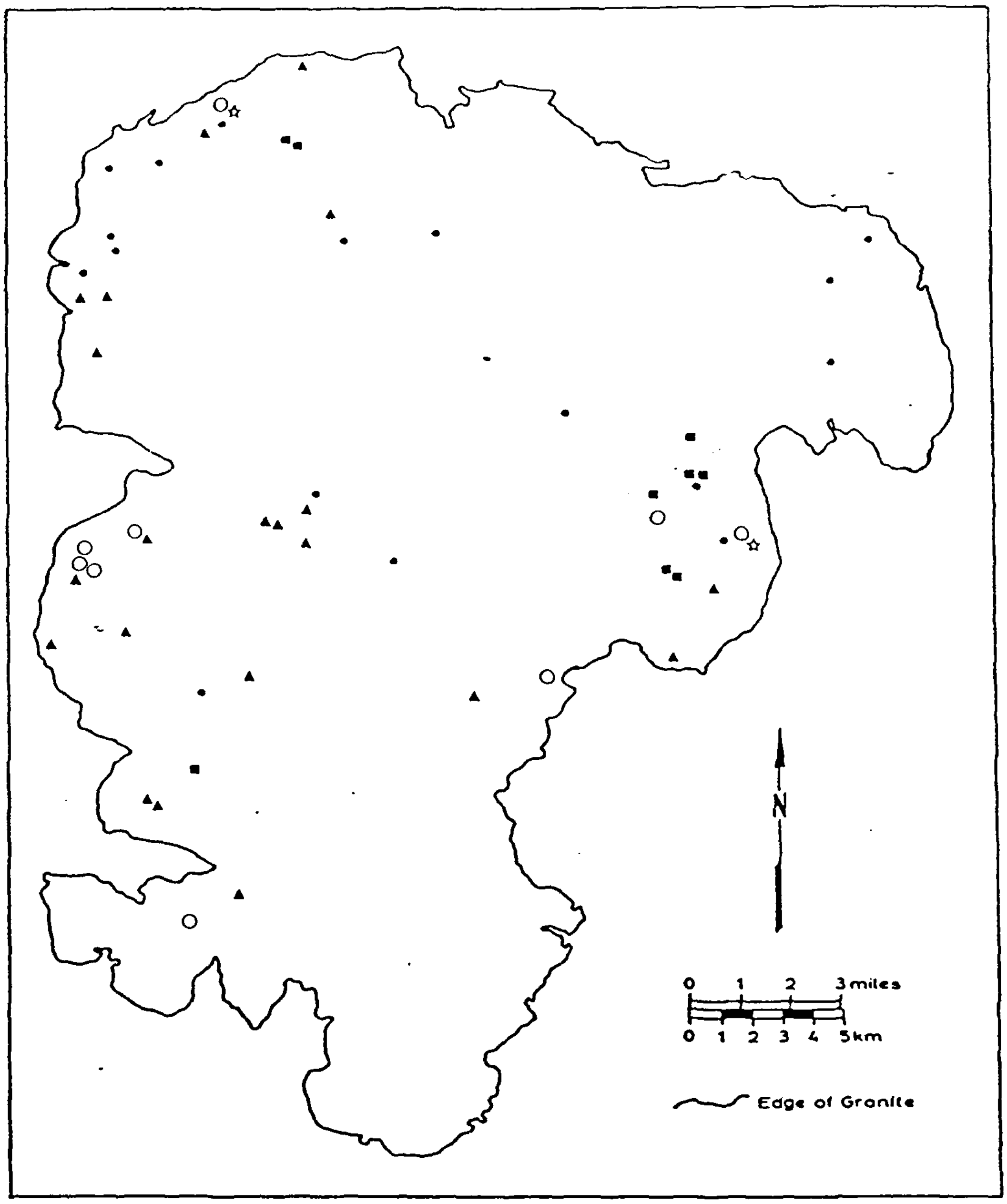

○ Group 1 • Group 2 ☆ Group 3 ■ Group 4

▲ Group 5

Figure 6

Figures 6A & B

Fig 6C & 6D

Figs 7 & 8